Crystal calorimeter readout electronics: inputs and discussions

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Specifications

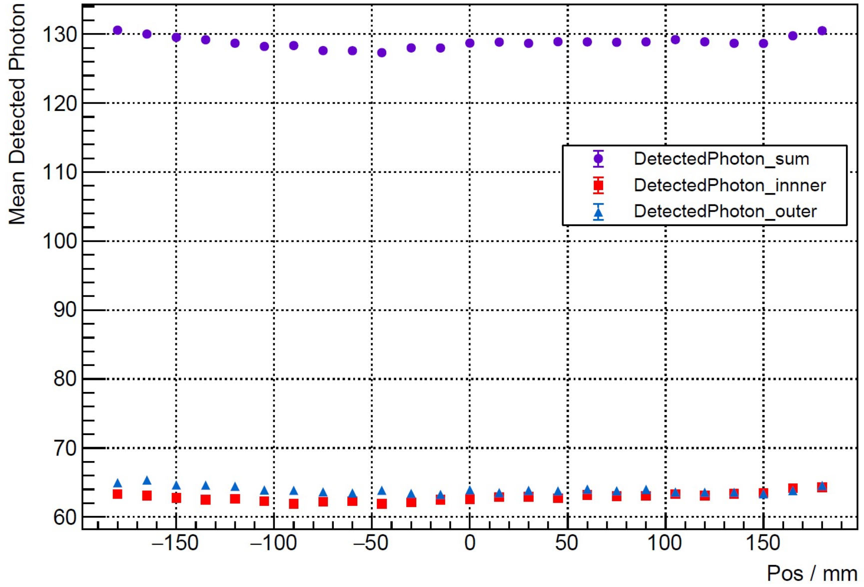
Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	Ensure EM resolution better than $2\%/\sqrt{E(GeV)}$
Dynamic range	0.1 - 10^3 MIP/channel	Deposited energy up to ~10 GeV per crystal
	(1 - 10^5 p.e./channel)	(With single photon calibration)
Energy threshold	0.1 MIP	Dependent on MIP Signal-to-Noise Ratio
Timing resolution	~400 ps @ 1 MIP	Geant4 simulation; for position reconstruction
Crystal non-uniformity	< 1%	Calibration precision
Temperature stability	Stable at ~0.05 ° C	CMS ECAL (PWO4)
Gap tolerance	~100 µm	Crystal calorimeter prototype

Crystal-SiPM timing resolution

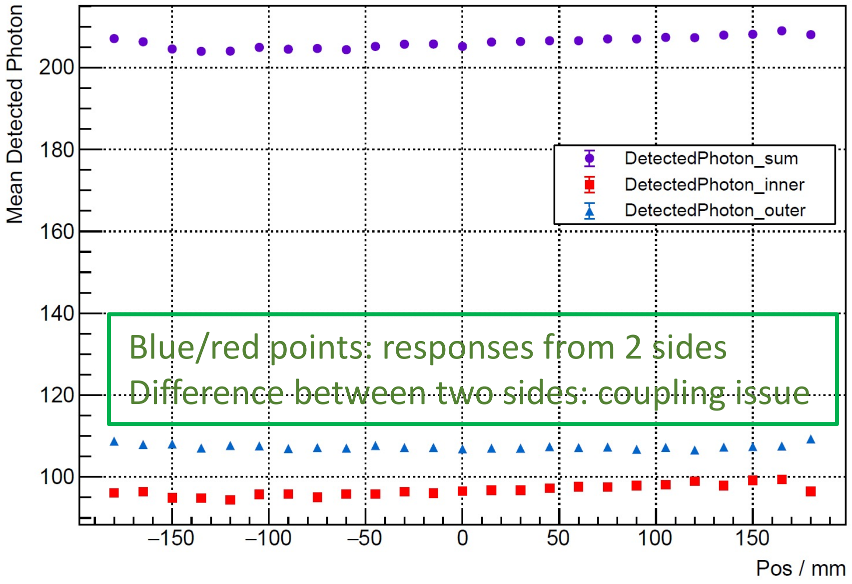
Crystal response uniformity

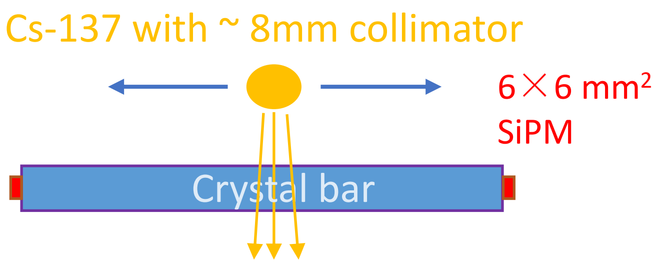
- 1×1×40 cm^3 BGO crystal with ESR wrapping
- Air/optical grease coupling
- Scan with Cs-137 radioactive source

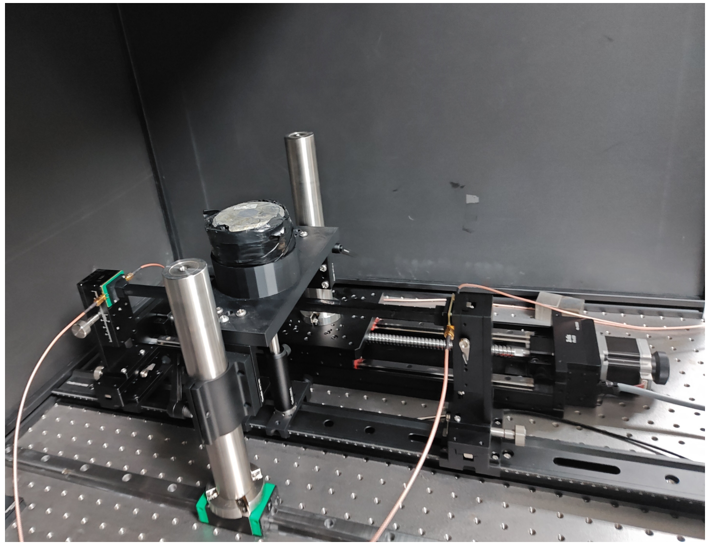
Response uniformity air-coupled



Response uniformity grease-coupled





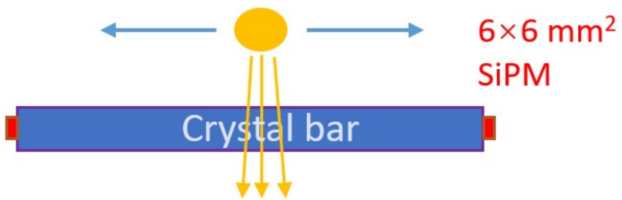


Automated scanning platform

- Generally good uniformity at ~2.5% level along a single bar
- Optical grease gives 59% improvement on detected photons
- Grease coupling is difficult to control

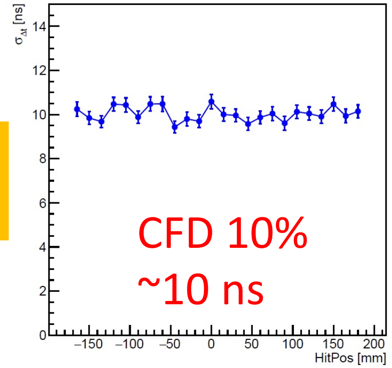
Time resolution: radioactive source and cosmic-ray tests

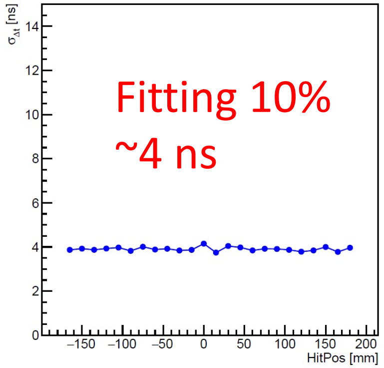
Cs-137 with ~ 8mm collimator



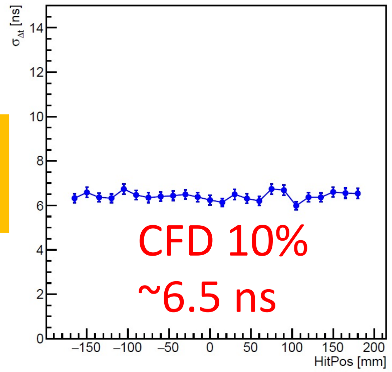
E_{dep}: 662 keV

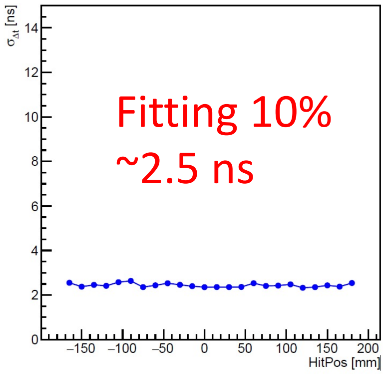
Time resolution
Air-coupled

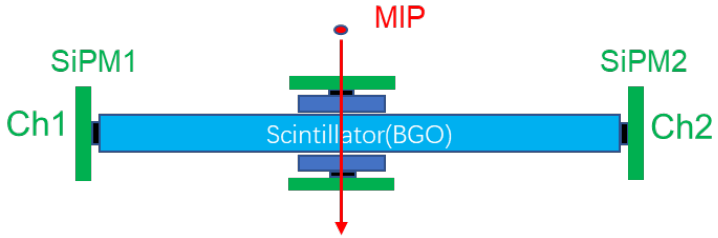




Time resolution
Grease-coupled

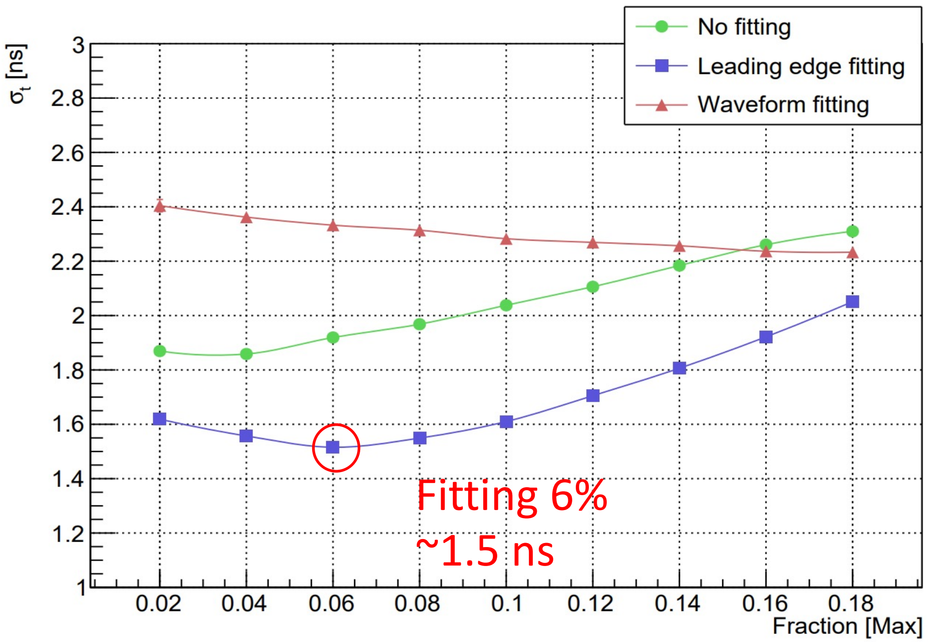






E_{dep}: ~8.9 MeV

Time Resolution vs. Fraction

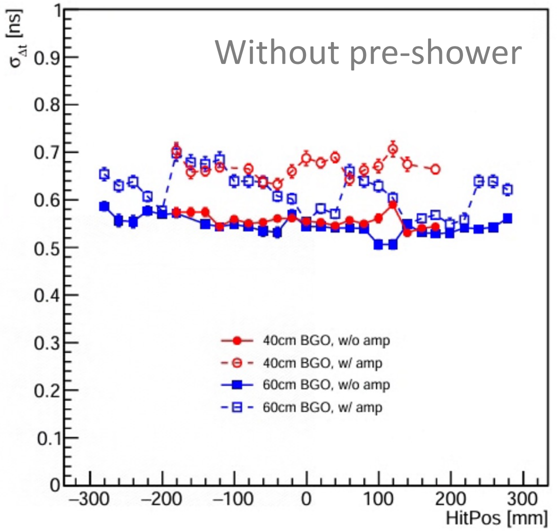


- Time resolution: ~4 ns at 662 keV (2.5 ns with grease), ~1.5 ns for MIP signals

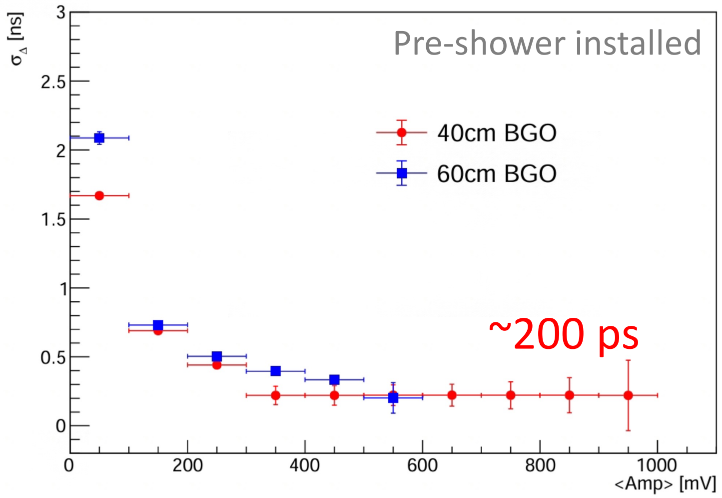
Time resolution: 2023 DESY beam-test

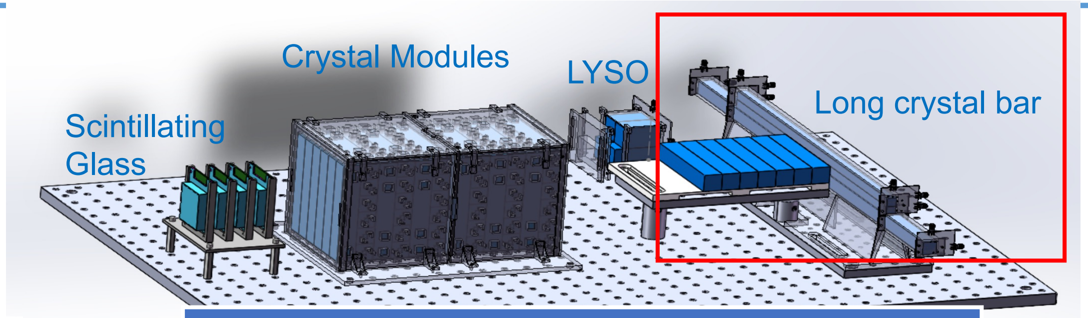
- (Quasi) 1-MIP response with 5 GeV/c electron beam
  - 1×1×40 cm^3 and 1.5×1.5×60 cm^3 BGO crystal
  - 25 µm pixel SiPM, DAQ 1.25GS/s DAQ

Time resolution: position scan

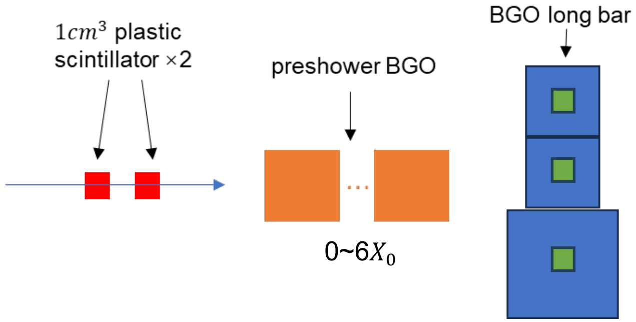


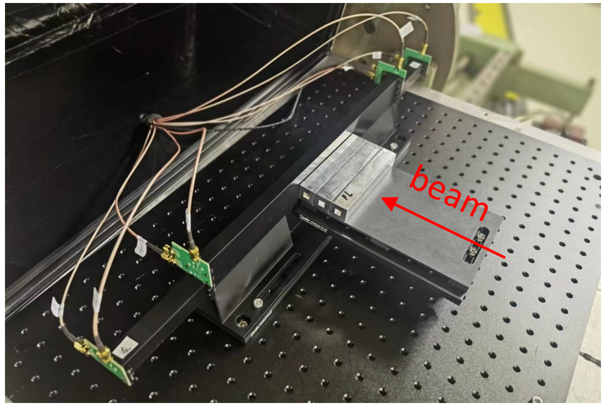
Time resolution vs signal amplitude





Overview of the 2023 DESY beam-test tasks





- Time resolution generally does not change significantly with position
- Time resolution varies with signal amplitude
  - Best result: 200 ps (40 cm BGO with >12 MIP signal, 60 cm BGO with > 20 MIP signal)

BGO and BSO timing resolution: Geant4 simulation

- 5GeV e-, $3 \times 3mm^2$ SiPM(HPK S14160-3015PS)

	Size	Decay time	Light yield	Time resolution	
10% CFD	$1 \times 1 \times 40cm^3$	60/300ns	8200ph/MeV	2.182ns	← BGO
	$1 \times 1 \times 6.95cm^3$	60/300ns	8200ph/MeV	0.966ns	
	$1 \times 1 \times 40cm^3$	25/100ns	8200ph/MeV	1.057ns	
	$1 \times 1 \times 40cm^3$	60/300ns	2000ph/MeV	5.005ns	
	$1 \times 1 \times 6.95cm^3$	25/100ns	2000ph/MeV	0.9534ns	

	Size	Decay time	Light yield	Time resolution	
10% Fit	$1 \times 1 \times 40cm^3$	60/300ns	8200ph/MeV	1.428ns	← BGO
	$1 \times 1 \times 6.95cm^3$	60/300ns	8200ph/MeV	0.8047ns	
	$1 \times 1 \times 40cm^3$	25/100ns	8200ph/MeV	0.7232ns	
	$1 \times 1 \times 40cm^3$	60/300ns	2000ph/MeV	3.028ns	
	$1 \times 1 \times 6.95cm^3$	25/100ns	2000ph/MeV	0.7432ns	

BGO and BSO timing resolution: Geant4 simulation

- 5GeV muon, $3{\times}3mm^2$ SiPM (HPK S14160-3015PS)

10% CFD	Size	Decay time	Light yield	MIP response (ch1+ch2)	Time resolution	
	$1{\times}1{\times}40cm^3$	60/300ns	8200ph/MeV	600p.e./MIP	3.691ns	← BGO
	$1{\times}1{\times}40cm^3$	25/100ns	2000ph/MeV	150p.e./MIP	4.244ns	

10% Fit	Size	Decay time	Light yield	MIP response (ch1+ch2)	Time resolution	
	$1{\times}1{\times}40cm^3$	60/300ns	8200ph/MeV	600p.e./MIP	2.212ns	← BGO
	$1{\times}1{\times}40cm^3$	25/100ns	2000ph/MeV	150p.e./MIP	2.291ns	

Summary

(1) faster timing requires larger signal amplitudes (i.e. steeper leading edge);

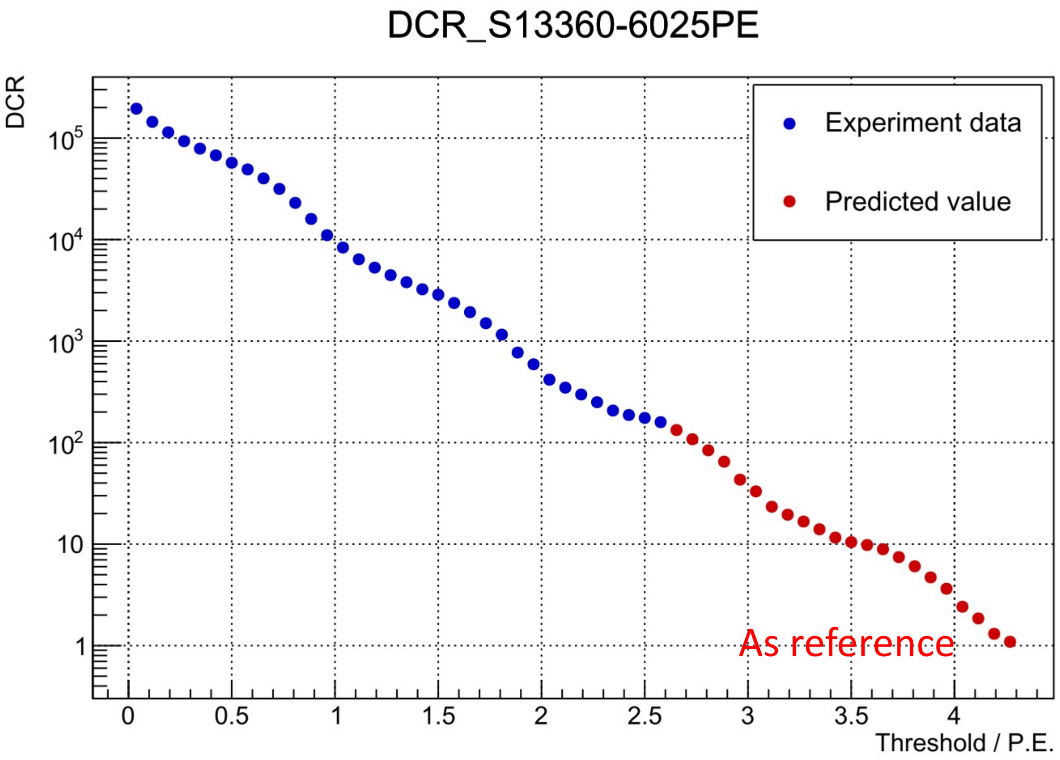
(2) electronics capable of resolving single photons also leads to a high slew rate of MIP signals

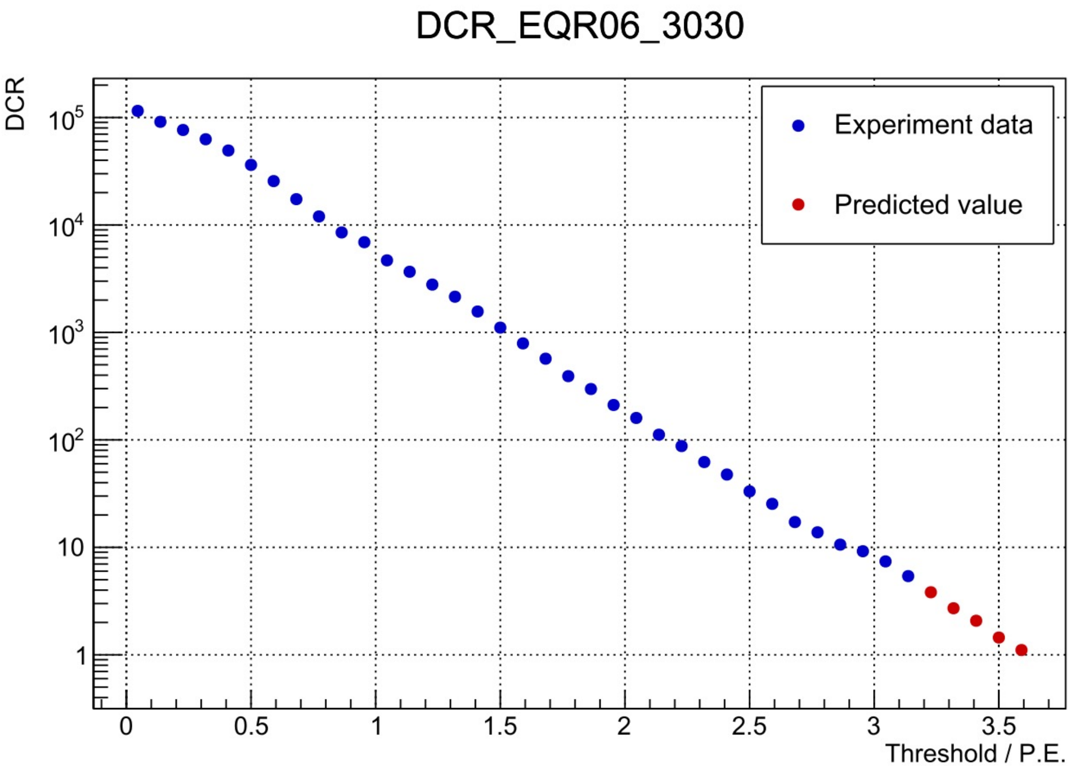
Discussions: timing performance would be degraded by excluding single photon calibration?

SiPM: single photon calibration?

SiPM noise rate vs trigger threshold: lab tests

- SiPM noise rate versus trigger threshold (in p.e.)

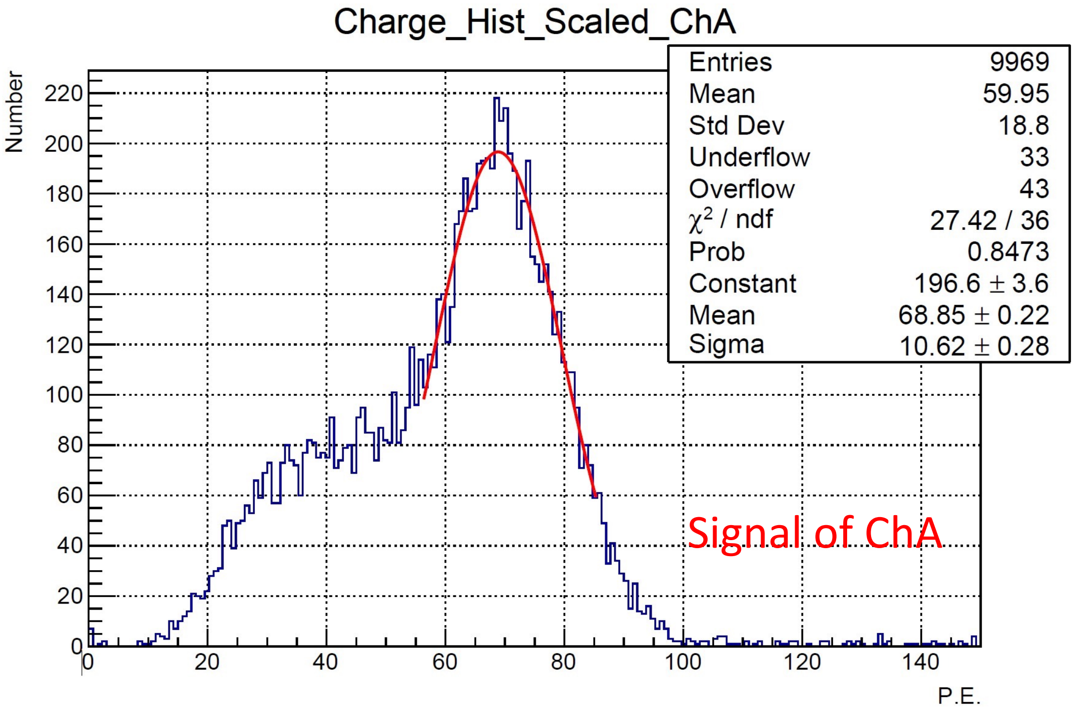


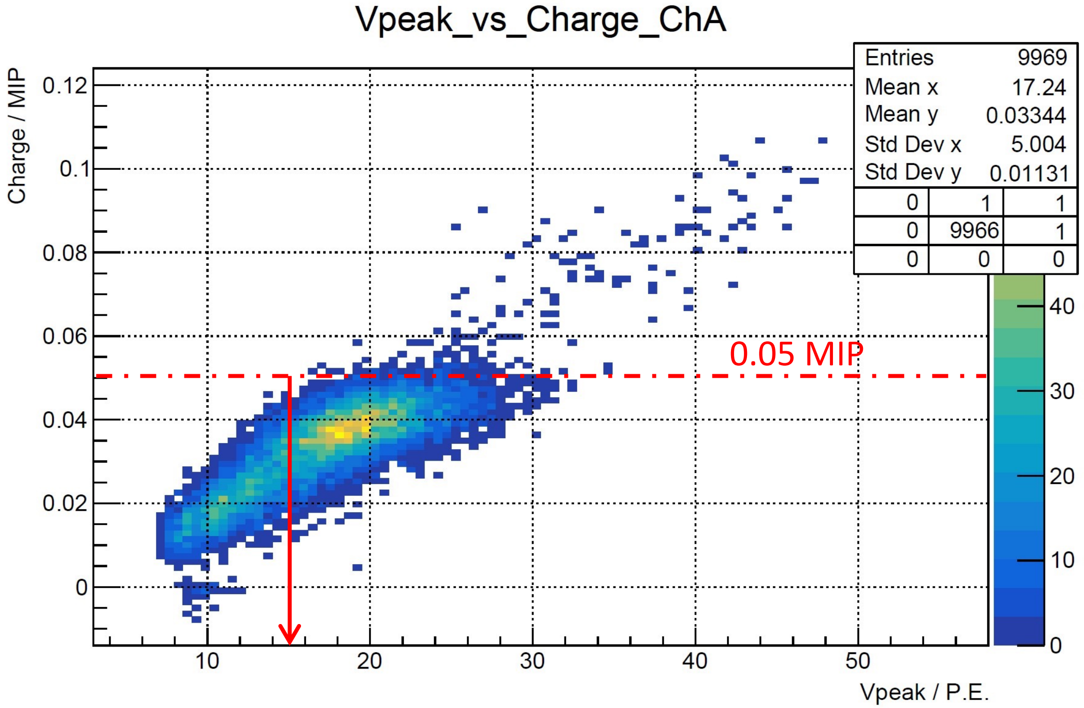


- Dark count rate can be lower than 1 Hz with low trigger threshold (in voltage)
- High sensitivity to low energy particles

Low-energy threshold for SiPM-crystal

- Crystal-SiPM waveform peak (voltage) is proportional to integrated charge (QDC)





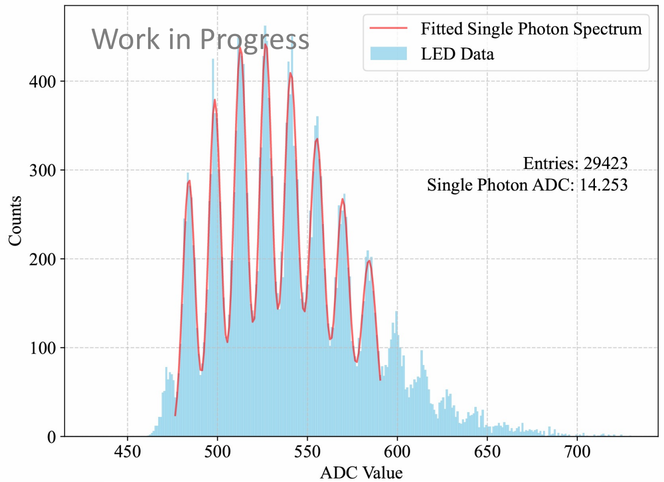
- 662 keV gamma corresponds to 0.07 MIP (2 channels)
- Requirement on dynamic range : 0.05~10^3 MIP

- Trigger threshold (in voltage) of 15 p.e. is feasible
  - SiPM noise level is negligible (<<1 Hz) at 15 p.e.
- Sensitivity to detect low energy particles
- Stringent requirement on dynamic range: 10^5 pixels

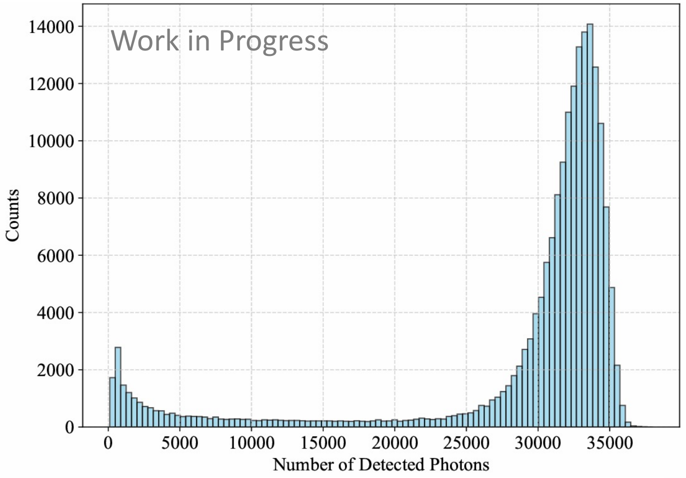
SiPM-ASIC studies: 2023 DESY beam-test

- Specs of state-of-art SiPM-readout chip (named MPT-2321)
  - Capability of single photon calibration; up to 1.6 nC; 50 ps TDC
- Beam-test of LYSO crystals, SiPMs and MPT2321
  - 5 GeV/c electron beam hits on LYSO crystal matrix
  - Readout with MPT chip + 25 µm pixel SiPM

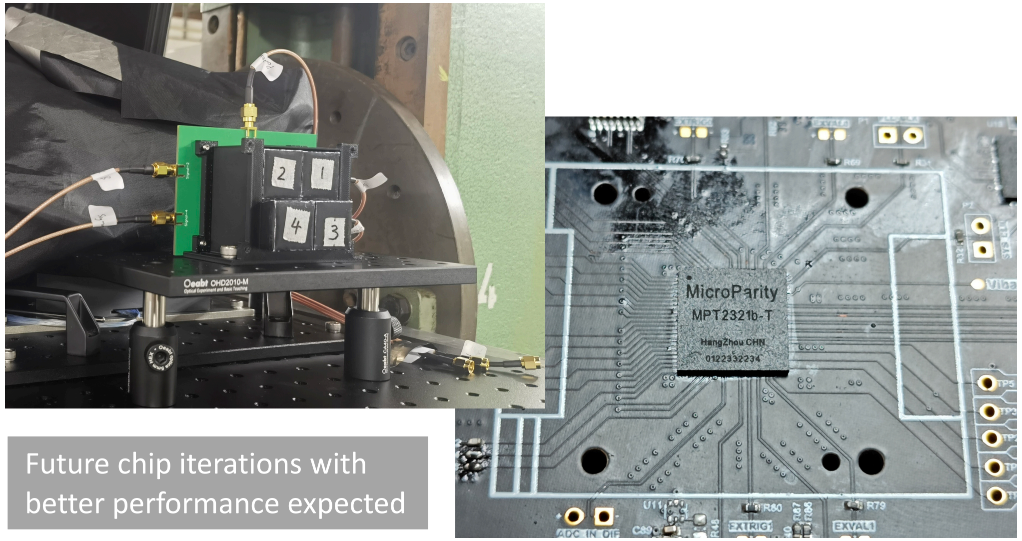
Overview of the 2023 DESY beam-test tasks



Highest gain: good S/N for single photon calibration



Lowest gain: capable for detecting ~33,000 photons



Future chip iterations with better performance expected

- MPT chip: a large dynamic range and high SNR for single photon calibration
- Dynamic range can be further extended: lower SiPM gain, shorter pixel recovery time

CALOR 2024 poster: Studies of a large dynamic range SiPM readout ASIC MPT2321-B

Considerations on single photon calibration

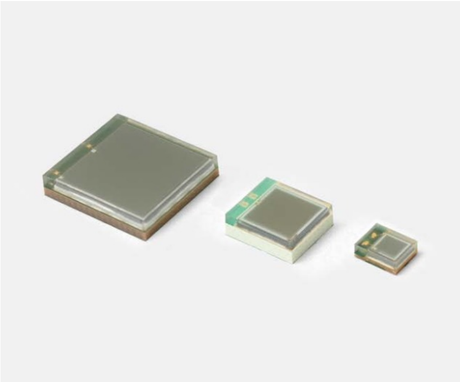
- What can we benefit from single photon calibration?
  - SiPM gain monitoring: long-term stability -> calorimeter calibration scheme
  - SiPM saturation effects (large signals) -> corrections crucial for energy reconstruction
  - Sensitivity to detect low-energy particles (on the order of 100 keV)
- Status on technical part
  - State-of-art ASIC capable to resolve single photons with >=~15um SiPM pixels
  - For SiPM pixel pitch <=10um, more stringent requirements on better SNR for low signals
- Can we exclude the requirement of single photon calibration?
  - Yes, since 0.1 MIP (trigger threshold) corresponds the minimum signal and thus the dynamic range requirement is less stringent, i.e. 0.1 MIP – 10^3 MIP
  - Also need to come up with dedicated calibration schemes for SiPM monitoring, and SiPM saturation corrections (which still requires single photon information)

Photo-sensors: SiPM vs APD

SiPM candidates with a large dynamic range

- $1.6 - 3.6 \times 10^5$ pixels in $6 \times 6\ \text{mm}^2$ HPK-SiPM

[HPK MPPC S14160-series data sheet]

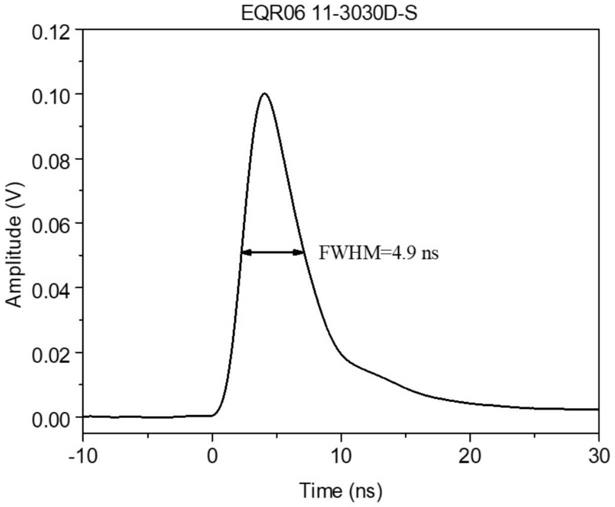


Type no.	Photosensitive area (mm)	Pixel pitch (μm)	Number of pixels	Fill factor (%)	Package	Window material	Window refractive index
S14160-1310PS	1.3 × 1.3	10	16663	31	Ceramic	Silicone resin	1.57
S14160-3010PS	3 × 3		89984				
S14160-6010PS NEW	6 × 6		359011				
S14160-1315PS	1.3 × 1.3	15	7284	49			
S14160-3015PS	3 × 3		39984				
S14160-6015PS NEW	6 × 6		159565				

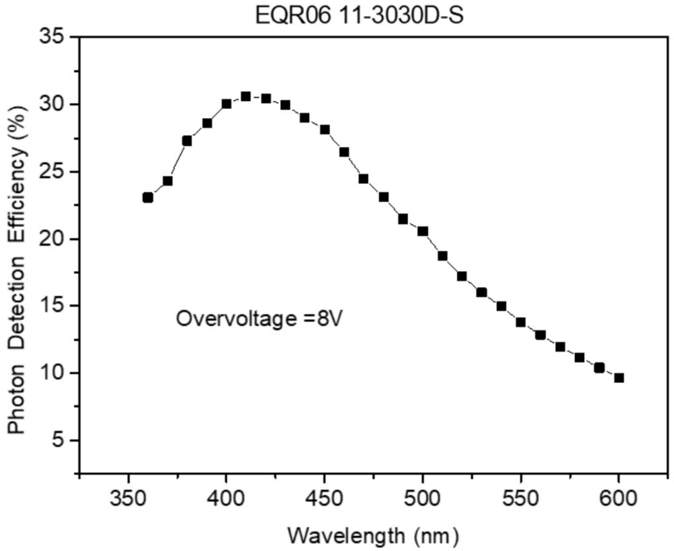
- 2.4×10^5 pixels in $3 \times 3\ \text{mm}^2$ NDL-SiPM

[NDL-EQR06 Series SiPM data sheet]

Type	EQR06 11-3030D-S
Effective Pitch	6 μm
Element Number	1×1
Active Area	3.0×3.0 mm^2
Micro-cell Number	27191 /mm^2
Typical Breakdown Voltage (V_B)	24.5 V
Temperature Coefficient for V_B	23 mV / °C
Recommended Operation Voltage	V_B + 8 V
Peak PDE @420nm	30 %
Gain	8.0×10^4
Dark Count Rate (DCR)	276 kHz / mm^2
Terminal Capacitance	5.1 pF / mm^2

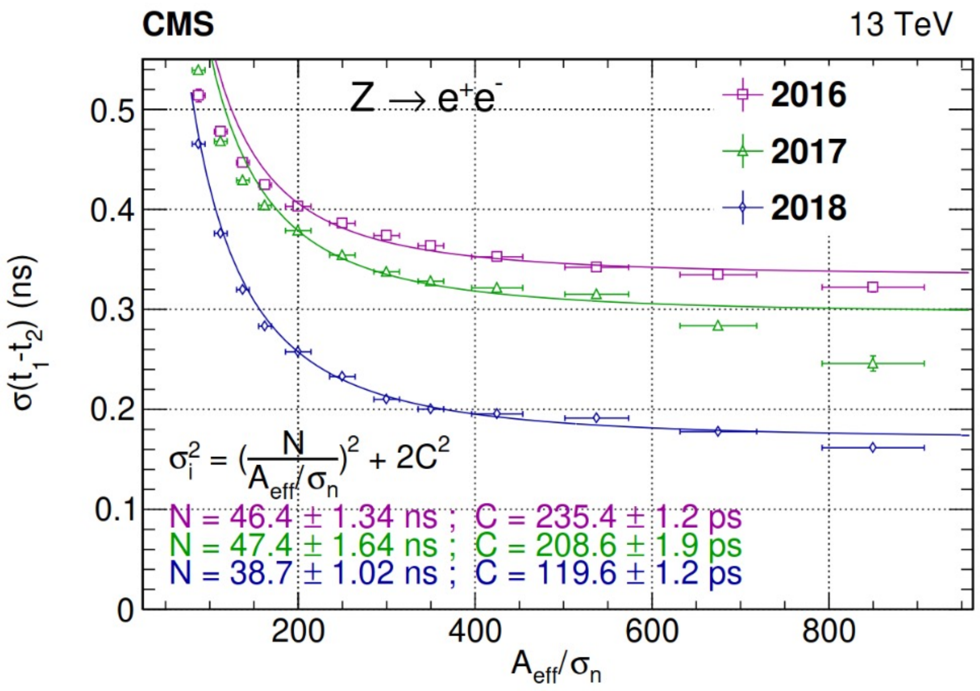


The single photoelectron pulse (amplified by a 60dB fast amplifier).



CMS ECAL: timing resolution

- CMS PWO4 calorimeter with APD readout
  - ~200ps timing resolution achieved only with large signals
  - Poor timing resolution at 1-MIP signal level: on the order of 10 ns



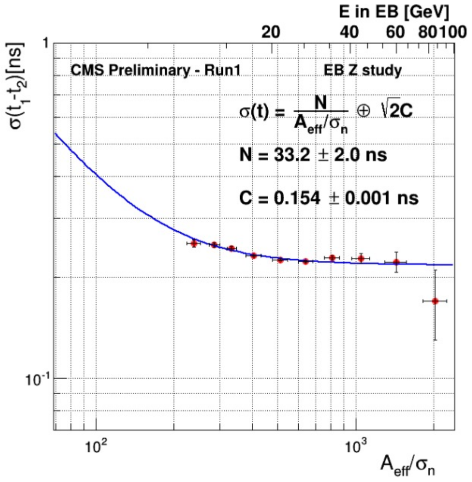


Figure 1. Barrel, electrons from Z decays: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

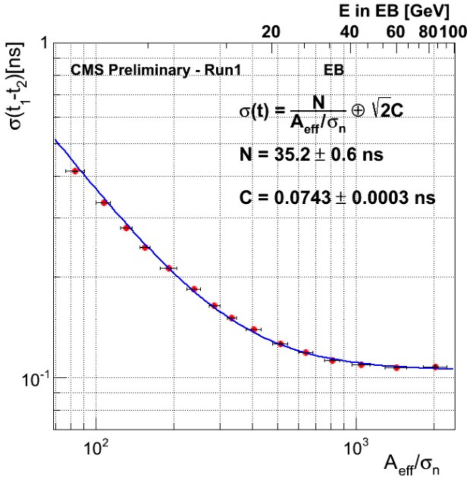


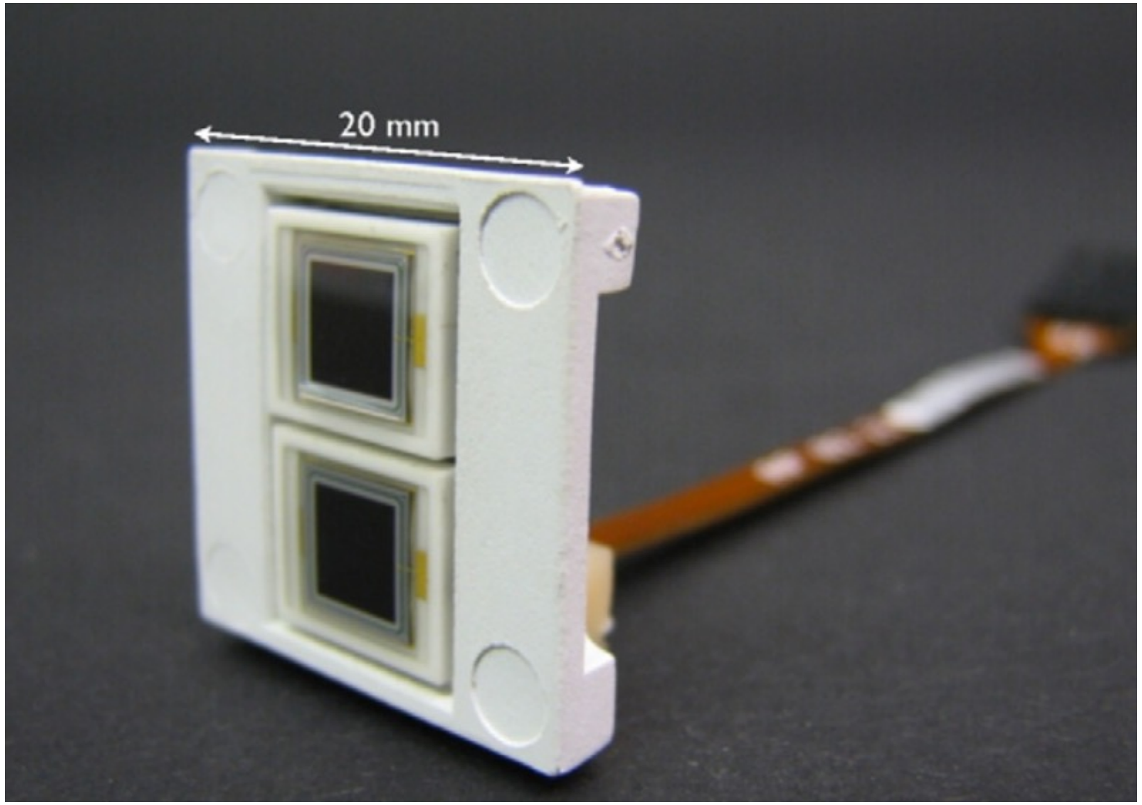
Figure 2. Study of neighboring crystals of a photon energy deposit: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

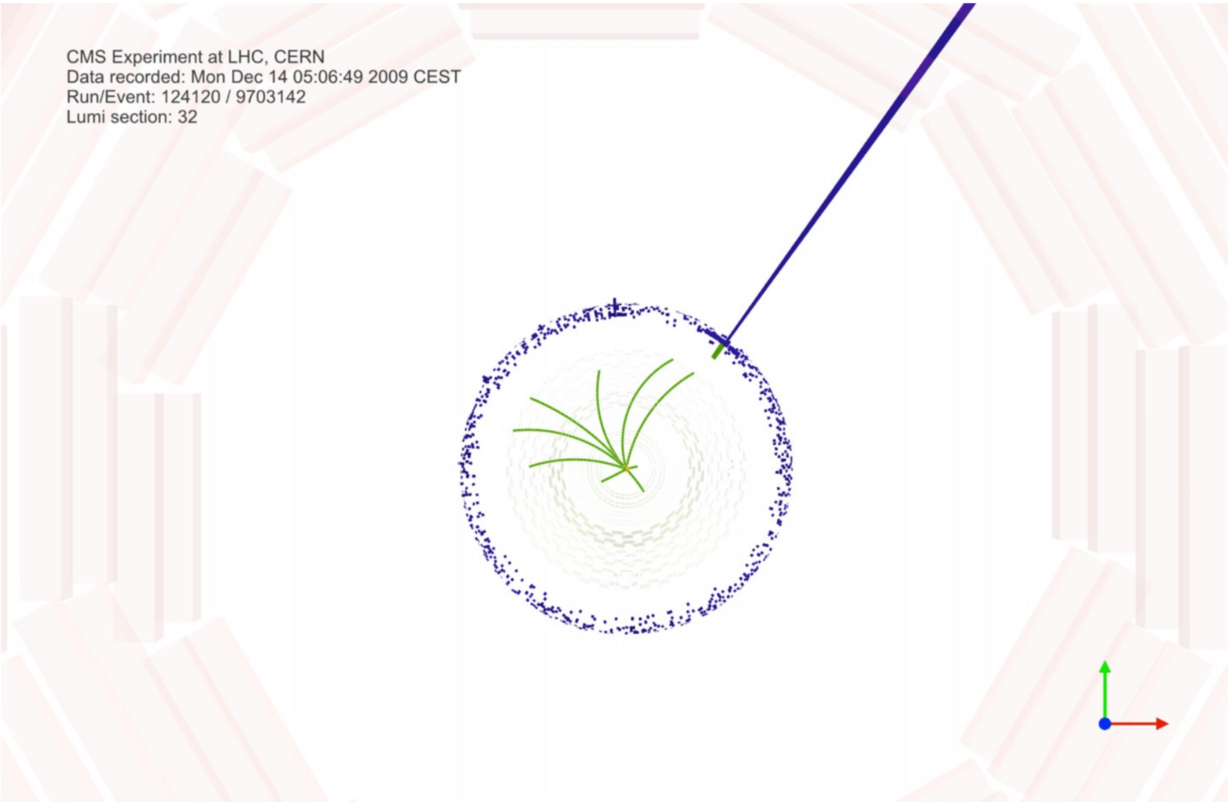
CALOR2024 Talk: https://indico.cern.ch/event/1339557/contributions/5915206/attachments/2859707/5002904/CALOR2024_PRESENTATION_ORLANDI.pdf

Timing performance of the CMS ECAL and prospects for the future, Daniele del Re 2015 J. Phys.: Conf. Ser. 587 012003

CMS ECAL with APD readout: spike events

- Ionisations directly in APD
  - Leading to a large energy deposition, equivalent to a high energy photon





Anomalous APD signals in the CMS Electromagnetic Calorimeter,
https://www.sciencedirect.com/science/article/pii/S0168900211019553

Other considerations on photosensors

- Industry applications
  - SiPM: wide applications in medical imaging, Laser-TOF (LiDar in autombiles)
    - Potentials in cost reduction and better QA/QC for mass production
  - APD: limited applications
    - Only limited applications in HEP, as far as I know
    - Would lead to a higher price tag than SiPM, given the same sensitive area

Summary on photosensor options

- SiPM and readout ASIC
  - Commercial SiPM product can cover up to 3.6×10^5 pixels
  - Existing ASIC can already cover a large dynamic range of 10^4
  - Beam test demonstrated quasi 1-MIP timing resolution of 500-600 ps
  - Wide applications in industry: potentials of cost effective and quality control

- APD in crystal calorimeter
  - CMS PWO ECAL: 1-MIP timing resolution on the order of ~10ns
  - CMS PWO ECAL: “Spike” events
  - Limited applications: unclear picture of cost reduction for mass production

Charge and time measurements: discussions

- Waveform sampling
  - Pros
    - Best timing performance: leading-edge waveform fitting
    - Capability to distinguish pile-up waveforms (-> largely depends on the occupancy level per channel)
  - Cons
    - Significantly huge data throughput and power consumption
    - Calorimeters in high granularity (millions of channels): possible bottlenecks due to boundary conditions for data, power and space

Personal remarks

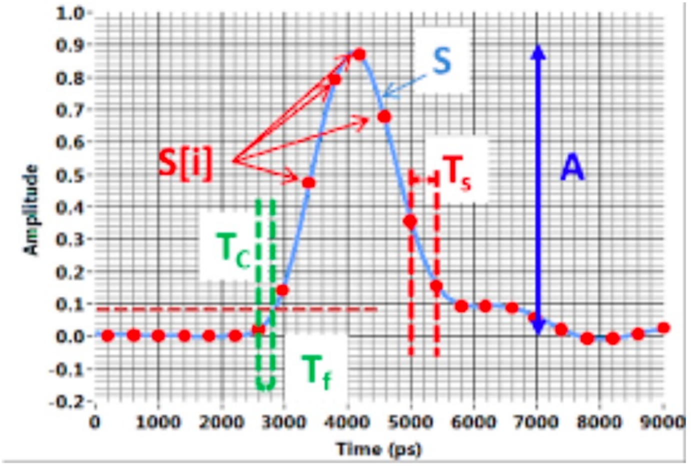
- As far as I know, there are no calorimeters at collider experiments that have used waveform sampling readout
- High granularity calorimeters are based on low-power chips that only extract key information on charge and timing

Christophe's talk at Pisa Meeting 2024

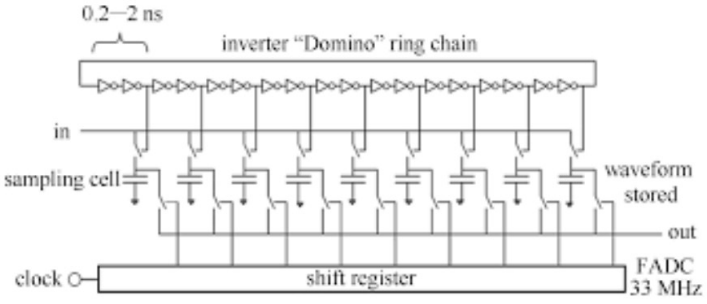
Waveform sampling

Ωmega

- Switched capacitor arrays (DRS4, Nalu, SPIDER…)
  - Pulse shape analysis
  - High accurcay timing, digital CFD
  - Sizeable power to provide GHz BW on large capacitance
  - large data volume



- Often used in off-detector electronics
  - Space and cooling available
  - Small/medium size detector readout and/or characterization
  - See LHCb calorimeter upgrade



- Upcoming R&D
  - Power reduction, Front-end integration
  - Data bandwitdth
  - Time walk correction, potentially best for ps accuracy